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Impact of treatment plant management on human health and ecological risks from wastewater irrigation in developing countries – case studies from Cochabamba, Bolivia

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ABSTRACT

Wastewater irrigation is a common practice in developing countries due to water scarcity and increasing demand for food production. However, there are health risks and ecological risks associated with this practice. Small-scale wastewater treatment plants (WWTPs) intend to decrease these risks but still face management challenges. This study assessed how the management status of five small-scale WWTPs in Cochabamba, Bolivia affects health risks associated with consumption of lettuce and ecological risks due to the accumulation of nutrients in the soil for lettuce and maize crops. Risk simulations for three wastewater irrigation scenarios were: raw wastewater, actual effluent and expected effluent. Results showed that weak O&M practices can increase risk outcomes to higher levels than irrigating with raw wastewater. Improving O&M to achieve optimal functioning of small-scale WWTPs can reduce human health risks and ecological risks up to 2 $\log_{10}$ DALY person^{-1} year^{-1} and to 2 $\log_{10}$ kg nitrogen ha^{-1} accumulated in soil, respectively.

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Wastewater irrigation; small-scale WWTPs; operation and maintenance; quantitative microbial risk assessment; ecological risks

Introduction

The global population is estimated to reach 9.1 billion by 2050. Feeding this population will require a 70% increase in food production, which in turn will require more water for irrigation (FAO 2009). Most of the increase in irrigation is likely to occur in developing countries, where three-quarters of global agricultural land are located, and where water scarcity is already a problem and is likely to increase due to climate change. As a consequence, farmers in most arid and semi-arid regions use wastewater irrigation to meet food demands (Alemu et al. 2019; United Nations World Water Assessment Programme 2017). This is particularly true in developing countries (Symonds et al. 2014), where an estimated 10% of arable land is irrigated with wastewater (United Nations World Water Development 2003). Farmers may often even prefer to use untreated or poorly treated domestic wastewater due to its nutrient content, which reduces the need for artificial fertilisers (Mojid et al. 2010), and also because it generally does not contain heavy metals (Uzen et al. 2016).

However, the potential benefits of reusing volumes of water and nutrients (nitrogen and phosphorus) to increase crop yields are accompanied by risks to ecosystems and human health

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(Siebe and Cifuentes 1995). The major ecological risks arise due to excess nutrients, which can cause eutrophication of surface water systems or negatively affect groundwater (Uzen et al. 2016; Jaramillo and Restrepo 2017). Irrigation with wastewater can also affect soil porosity by disturbing normal microbial activity (Toze 2006). The major health risks in developing countries are due to wastewater-borne pathogens (Hamilton et al. 2007; Qadir et al. 2010), particularly viruses, pathogenic bacteria and helminth eggs (Gumbo et al. 2010; Sharafi et al. 2017). The number of diarrhoeal outbreaks associated with pathogenic protozoa in wastewater is rather low in developing countries (Bos et al. 2010). Viruses are a concern for water reuse, because of their persistence in the environment and low-dose infectivity (Moazeni et al. 2017). Bacteria are a concern because most treatment systems in developing countries do not aim for significant bacteria removal from wastewater (Bos et al. 2010). Waterborne helminths are a major concern in developing countries because they are highly prevalent, wastewater is informally reused and they are persistent in the environment (Mara and Sleigh 2010; Qadir et al. 2010).

Implementing WWTPs is the conventional way of managing such risks. However, both lack of financial and technical resources in developing countries are major challenges for implementing wastewater treatment strategies, monitoring to identify insufficient treatment plants and hampering sustainable operation (Massoud et al. 2009; Qadir et al. 2010; Noyola et al. 2012). The major issues affecting sustainable functioning of small-scale wastewater treatment plants (WWTPs) in developing countries are inappropriate design or selection of technology (Bdour et al. 2007; Brissaud 2007; Massoud et al. 2009; Mara 2013), poor operation and maintenance (Singhirunnusorn and Stenstrom 2009; Noyola et al. 2012), lack of technical expertise (Ujang and Buckley 2002; Noyola et al. 2012) and lack of monitoring (Massoud et al. 2009; Cossio et al. 2017). Recognizing the complexity of the situation, the WHO has proposed an approach in which several risk management alternatives (conventional and non-conventional) are compared in terms of risk outcomes and feasibility of their implementation (WHO 2006). Since then, many studies have been carried out to assess different strategies for management of risks from irrigation with wastewater (Keuckelaere et al. 2015). However, the published risk assessment studies assume either no wastewater treatment at all, or treatment processes that function adequately. Thus, the effect of poor management of WWTPs on risks from reusing wastewater for irrigation is yet to be assessed, as well as the potential of improving O&M of existing treatment plants as an alternative to manage risks from wastewater irrigation. Accordingly, the aim of this study was to identify how the management of small-scale WWTPs effect the ecological and health risks from using wastewater for irrigation. Specific objectives were to: (1) assess the technical, operational and maintenance status of five small-scale WWTPs in Cochabamba, Bolivia, using semi-quantitative criteria; (2) use quantitative risk assessment models to estimate human health risks (gastroenteritis) associated with lettuce consumption and environmental risks (excessive nutrient release to soil) caused by irrigating lettuce and maize crops with wastewater from the five WWTPs; and (3) discuss whether poor WWTP management increases the risks and suggest recommendations to reduce the risks in different scenarios.

Materials and methods

Study area and characteristics of the small-scale wastewater treatment plants

The study area is located in the valley of Cochabamba, Bolivia, where farmers reuse wastewater for irrigation due to water scarcity (Huibers et al. 2004; Perez-Mercado et al. 2018). Five small-town WWTPs were studied (Case 1-5), all of which use common technologies implemented in small-towns in Bolivia (i.e. stabilisation ponds, Imhoff tanks, septic tanks, filters and, upflow anaerobic sludge blanket (UASB)) (Ministerio de Medio Ambiente y Agua 2013). Table 1 summarises the characteristics of the five WWTPs (for treatment schemes, see Supplementary Material).

Table 1. Characteristics of the WWTPs used in this study.

Code[1]	Case 1-UFP	Case 2[II]-UF	Case 3-P	Case 4-I	Case 5-I
Population equivalent	3344	7980	7000	3500	575
Flow rate[III] (m^3/d)	124	319	264	149	54
Process units	Pre-treatment 1 UASB reactor 2 Biofilters 1 Maturation pond Sludge drying bed	Pre-treatment 1 Storage tank 1 Mechanical screen 5 Grease chambers 5 UASB reactors 10 Biofilters Sludge drying bed	Pre-treatment 2 Anaerobic ponds 2 Facultative ponds 4 Maturation ponds	Screens 1 Storage tank 2 Imhoff tanks	Imhoff tank
Treatment level	Tertiary	Secondary	Tertiary	Primary	Primary

[I]Case number, followed by letters representing the main treatment process/es: U = UASB reactor; F = biofilter; P = stabilisation ponds; I = Imhoff tank.
[II]Case 2 has five treatment lines after mechanical screening, only one of which was sampled.
[III]Flowrates were measured using the volumetric method.

Data collection

Chemical and microbial parameters of wastewater

Grab samples of influent and actual effluent were collected from the five WWTPs and analysed for: biochemical oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), nitrates (N-NO_3), total organic nitrogen (Tot N), ammonia (N-NH_4^+), total phosphorus (Tot P), phosphate (P-PO_4), faecal coliforms (FC), coliphages (i.e. F^+ specific and somatic) and helminth eggs. All sampling and analyses were performed using standard methods (APHA 1998). Three sampling campaigns were performed for each of the five case studies, two campaigns during the dry season and one during the rainy season. Limited resources, difficulties in accessing the WWTPs and long distances to the sites made it difficult to implement a larger number of sampling campaigns. Therefore, data from previous studies were used to complement the original data set. All data are shown in Supplementary Material (Tables S1 and S2).

Management information on the WWTPs

Semi-structured interviews with managers of the five WWTPs were conducted to assess the technical and operational status of the WWTPs. The interviews included closed and open-ended questions. Following qualitative research methods (Flick 2009), the data obtained were triangulated with field observations regarding the functionality of the technologies and data obtained in informal interviews with other staff involved in WWTP management. All data obtained are shown in Supplementary Material (Table S3).

Assessment of WWTP status

WWTP status was assessed using three main criteria: (i) current performance, (ii) technological potential, and (iii) operation and maintenance (O&M), with each criterion based on a set of indicators rated on a scale of 0 to 2 according to the assessment criteria in Table 2 and Supplementary Material ('Management assessment'). The assessment of indicators for criteria 1 and 2 relate to general requirements for WWTPs, while assessment of indicators in criterion 3 (O&M) relate to technology-specific requirements (for details, see Supplementary Material).

For each WWTP, the total scores were normalised to a scale from 0 to 1 by dividing the sum of scores within each criterion by the maximum score in that criterion. A normalised score of 1 indicates that all requirements were completely fulfilled. The final score shown for each WWTP is the mean normalised score (i.e. sum of normalised scores divided by 3).

Table 2. Criteria, indicators and scoring rules used in assessing WWTP management.[I]

Scores	Rules for scoring
Criterion 1: Current performance	
Indicator 1: Meets BOD discharge requirements in country *Indicator 2*: Meets TSS discharge requirements in country	
Scores	Rules for scoring
0	if the measured effluent does not meet the limits/targets in any sampling campaign.
1	if the measured effluent meets the limits/targets in at least 50% of all sampling campaigns and the mean does not exceed the limit by 50%.
2	if the measured effluent meets the limits/targets in 100% of sampling campaigns.
Criterion 2: Technological potential	
Indicator 3: Potential of current technology to reach the health-based target of 6 $\log_{10}$ pathogen reduction for unrestricted irrigation. *Indicator 4*: Potential of current technology to reach the health-based target of ≤1 helminth egg per litre in the treated wastewater for unrestricted irrigation.	
Scores	Rules for scoring
0	if the WWTP theoretically cannot achieve the target for wastewater reuse
1	if the WWTP theoretically can achieve the target for wastewater reuse when operating at a high removal efficiency.
2	if the WWTP theoretically can achieve the target for wastewater reuse when operating at a low removal efficiency.
Criterion 3: Operation and maintenance	
Indicator 5: Meets required level and availability of technical expertise needed for optimal O&M (technology-specific). *Indicator 6*: Performs required O&M activities and frequency in pre-treatment (technology-specific). *Indicator 7*: Performs required O&M activities in the main process units (technology-specific). *Indicator 8*: Performs required long-term maintenance activities in the main process units (technology-specific). *Indicator 9*: Has the required monitoring system to ensure optimal O&M (technology-specific).	
Scores	Rules for the scoring
0	if requirements for optimal O&M are not fulfilled.
1	if requirement for optimal O&M are partly fulfilled.
2	if requirements for optimal O&M are fulfilled.

[I]For details, see Supplementary Material ('Management assessment').

Criterion 1: current performance

The current performance of the WWTPs was scored based on two indicators: whether they met the requirements on BOD and TSS discharge into receiving waterbodies. These are typical parameters to evaluate the performance of WWTPs with primary and secondary treatment levels that are treating domestic wastewater (Colmenarejo et al. 2006; Muga and Mihelcic 2008; Singh et al. 2015). This indicates their ability to remove basic constituents for which they were originally designed (Metcalf 2014). The statutory discharge limits in Bolivia are 80 mg/L for BOD and 60 mg/L for TSS (MMAyA 1995).

Criterion 2: technological potential

The potential of current technologies used in the WWTPs to reduce risks was scored based on microbial parameters, using two indicators: whether they met health-based targets for unrestricted irrigation recommended by the World Health Organisation (2006), i.e. a 6 $\log_{10}$ reduction of faecal coliforms (FC) and ≤1 helminth egg per litre in treated wastewater. In the cases of nitrogen and phosphorus, there are no standard effluent requirements for the specific purpose of irrigation, thus they were not included. FC and helminth eggs are typically used when assessing treatment processes implemented to reduce health risks for wastewater reclamation (Bixio et al. 2008; Stenström et al. 2011; Noyola et al. 2012). The assessment of FC removal was based on theoretical low and high removal efficiencies for the current technologies. The assessment of helminth egg removal involved estimating an influent value based on measured data (95th percentile of raw water datasets from all WWTPs), to account for peaks in microbial concentrations, and then applying theoretical low and high removal efficiencies for the current technologies.

Criterion 3: operation and maintenance

The O&M of WWTPs was scored based on five indicators (Table 2): (i) required level and availability of technical expertise needed for optimal O&M of the specific WWTP, (ii) required O&M activities and frequency in pre-treatment, which is critical for following processes to work optimally, (iii) required regular O&M activities to ensure WWTP functionality, (iv) long-term maintenance activities in the main process units, e.g. important repairs or replacements and (v) a monitoring system that can support optimal O&M, since lack of monitoring is often a key issue in small-scale WWTPs (Cossio et al. 2017).

Quantitative assessment of microbial risks from lettuce consumption

The microbial risks for consumers of lettuce irrigated with wastewater from the studied sources were assessed using the quantitative microbial risk assessment (QMRA) approach developed by Haas et al. (2014). QMRA is a probabilistic modelling procedure to estimate the risk to human health for specific scenarios, based the concentration of the significant pathogen(s), the pathway of exposure and the infectivity of the pathogen. All input variables are defined as probability distributions to account for uncertainties in the input data and Monte Carlo simulations used to estimate the probability of adverse health effects.

Hazard identification and exposure scenario

Enterovirus, *Salmonella* spp. and *Ascaris lumbricoides* were chosen as microbial hazards, as they are known to be found in high concentrations in wastewater, are persistent in the environment and are responsible for many waterborne infections in developing countries (World Health Organization 2006; Bos et al. 2010; Sharafi et al. 2017). While there is a lack of specific data regarding the incidence of these pathogens in the Bolivian population, they are major contributors to the global annual disease burden.

The health risks were assessed for exposure scenarios of consumption of lettuce that was furrow-irrigated with raw wastewater, actual effluent or theoretical effluent (i.e. achievable effluent quality if the WWTP is adequately managed) from the five treatment plants. The microbial load on lettuce was calculated based on irrigation management practices used by lettuce farmers from Cochabamba (12–24 mm of water applied by furrow every 2 days during the 60-day lettuce culture period) (Tarqui Delgado et al. 2017; Perez-Mercado et al. 2018). The doses of ingested pathogens were estimated based on the consumption of one portion of unwashed, uncooked lettuce, consumed three times per week during the season when irrigation is needed (Verbyla et al. 2016). It was assumed that the three weekly portions came from the same lettuce head. The irrigation period was assumed to be 43 weeks between March and December, in the worst-case scenario of a dry year. In total, 129 exposures/year and person were assumed.

Microbial risk models and input data

The concentrations of Enterovirus, *Salmonella* spp. and *A. lumbricoides* in irrigation water were estimated using the concentrations of indicator organisms measured in this study and ratios reported in previous studies. Using ratios to estimate the concentration of pathogen is a common procedure for calculating Enterovirus, *Salmonella* spp. and *Ascaris lumbricoides*, as reviewed by Keuckelaere et al. (2015). Enteroviruses were estimated using a ratio Coliphages:Enteroviruses of 10^3:1 (Costán-Longares et al. 2008); *Salmonella* spp. were estimated using the ratio Fecal Coliforms: *Salmonella* spp. of 10^6:1 – 10^8:1 (WHO 2006); and *Ascaris lumbricoides* was estimated using the ratio Helminth eggs: *Ascaris* spp. of 1:0.65 (Perez-Mercado et al. 2018), where all *Ascaris* spp. eggs were assumed to be *Ascaris lumbricoides*. In the simulations, the concentrations of pathogens in the expected effluents were calculated based on the concentrations of pathogens in raw wastewater and the expected removal efficiencies of each WWTP. The concentrations of pathogens in raw wastewater and actual effluent are based on measured data (Table S1), for *Ascaris lumbricoides* and Fecal Coliforms, complemented with data from previous studies (Table S1, footnote and Table S2, respectively). Each data set was assumed to represent lognormal distributions, and the calculated parameters were used to define the probability distributions (Table S5). All the input data can be found in Supplementary Material (see Table S5).

The dose of enterovirus per serving was calculated as

$$\mathrm{d_E} = \ \mathrm{V}_P\ .\mathrm{I.}\ \mathrm{C_{EW}}\ .\ \mathrm{e}^{-(\mathrm{k_E}\ .\mathrm{rs.Sh.T-withhold})} \tag{1}$$

where d_E = dose of enterovirus (PFU serving^{-1}), V_P = volume of irrigation water caught by product (mL g^{-1}), I = consumption per capita (g serving^{-1}), C_{EW} = concentration of enterovirus in the irrigation water, k_E = post-irrigation decay of enterovirus due to energy flux from solar radiation (log10 KJ^{-1} m^2), rs = solar radiation (KJ h^{-1} m^{-2}), Sh = sunny hours per day (h day^{-1}), and T-withhold = time between irrigation and ingestion (day).

The dose of *Salmonella* spp. per serving (d_{Salm}, in cfu serving^{-1}) was calculated as

$$\mathrm{d_{Salm}} = \ \mathrm{V}_P\ .\mathrm{I.}\ \mathrm{C_{SW}}\ .\ 10^{-(\mathrm{k_S}\ .\mathrm{Sh.T-withhold})} \tag{2}$$

where C_{SW} = concentration of Salmonella spp. in the irrigation water (eggs mL^{-1}), and k_S = post-irrigation decay of *Salmonella* spp. due to solar radiation ($\log_{10}$ h^{-1}). Unlike enterovirus, no data about *Salmonella* spp. decay due to energy flux from solar radiation in vegetable surfaces was found. Therefore, only decay from solar radiation as a function of time was included in the dose model.

The dose of *Ascaris lumbricoides* per serving (d_H, in eggs serving^{-1}) was calculated as

$$\mathrm{d_H} = \ \mathrm{V_P} \times \ \mathrm{I} \ \times \ \mathrm{C_{AW}} \tag{3}$$

where C_{AW} = concentration of *Ascaris lumbricoides* in the irrigation water (eggs mL^{-1}).

Dose–response models were used to estimate the weekly risks of infection for each of the studied pathogens (i.e. P_{Ent}, P_{Sal}, P_{Asc} for weekly probabilities of infections due to enterovirus, *Salmonella* spp. and *Ascaris lumbricoides* respectively). The models used and the corresponding pathogens were: the exponential model for enterovirus (Symonds et al. 2014) (Equation 4), and the simplified beta-Poisson model (Equation 5) for *Salmonella* spp. (Dalahmeh et al. 2016) and *Ascaris lumbricoides* (Mara and Sleigh 2010).

$$\mathrm{P}_{Ent} = 1 - \ e^{(-\mathrm{k.}\ \mathrm{d_E}\ .\mathrm{W})} \tag{4}$$

where k is the model parameter representing infectivity constant of enterovirus and W is the number of servings per week,

$$P_{Sal},\ P_{Asc} = 1 - \left[1 + \frac{W.\ d_m}{N_{50}}\left(2^{1/\propto} - 1\right)\right]^{-\propto} \tag{5}$$

where α is the infectivity constant, N_{50} is the median infection dose, and d_m is the ingested dose per serving, expressed as d_{Salm} in case of *Salmonella* spp. and d_H in case of *Ascaris lumbricoides*.

The annual risk of infection ($P_{I\text{-}annual}$) for each pathogen was used to estimate the annual burden of disease (DALY). The annual risk of infection is:

$$P_{I-annual} = 1 - \prod\nolimits_{k=1}^{np} (1 - P_k)^{nq} \tag{6}$$

where P_k = the periodic infection probability (P_{Ent}, P_{Sal}, or P_{Asc}) in the k_{th} week, np = number of exposure periods per year (i.e. 43 weeks), nq = the period (days) over which the assumption is assumed to be constant (i.e. it was assumed as 1), assuming statistical independence of periodic infection probabilities.

The annual burden of disease measured as disability-adjusted life years (DALY) was estimated as:

$$DALY = P_{I-annual} \times B \times S_f \times P_{I:I} \tag{7}$$

where B is the burden of disease per illness case, $P_{I:I}$ is the proportion of infections that become symptomatic (illness), and S_f is the proportion of people susceptible to the disease (assumed as 1 for all the studied diseases, meaning that the whole population is susceptible). All input data: the type of distribution, distribution parameters and point estimates used in Equations 2–7 are presented with references in Supplementary Material (Table S5).

Assessment of excess nutrient risks

The deficit or excess of nutrients applied to soil through wastewater irrigation was estimated by comparing the amount of available forms of nutrients applied in wastewater per unit surface with crop requirements during the growing season (Pescod 1992). Like for QMRA, input variables were defined as probability distributions and Monte Carlo simulations were used to estimate the probability of either deficit or excess nutrients.

Hazard identification and exposure scenario

Phosphorus and nitrogen were chosen because both are considered major agents of eutrophication and have been found in wastewater-polluted streams used for irrigation in Bolivia (i.e. concentrations of up to 48 mg PO_4 L^{-1} and 8 mg NO_3^- L^{-1}). Further, eutrophication has been detected in waterbodies close to urban areas (Acosta and Ayala 2009; Contraloria General del Estado 2011; Archundia et al. 2017; Morales et al. 2017). Although wastewater irrigation reduces the need for fertiliser application, nutrients can be washed off the soil to groundwater or shallow waterbodies if applied in excess (Connor et al. 2017). Most farmers from Cochabamba do not adapt their fertiliser use to the nutrient content in wastewater (Perez-Mercado et al. 2018), thus leading to potential excess.

For each of the five WWTPs, the excess nutrient risks were assessed for one season of each crop (lettuce and maize) irrigated with raw wastewater, actual effluent or theoretical effluent. The assessments were based on the lettuce cultivation scenario described above and on irrigation practices reported for maize cultivation in Cochabamba (furrow irrigation six times during the 90-day culture period, with first irrigation 75-90 mm, second irrigation 70-100 mm and the third-sixth irrigation 55-80 mm), as reported by Rocha (2003). Thus, a total of 29 and six irrigations per season were assumed for lettuce and maize, respectively.

Excess nutrient risk models and input data

The chemical data measured at the WWTPs were used to calculate the ratio of available/total forms of the nutrients (i.e. PO_4-P/Tot P and NH_4^+-N/Tot N; nitrate concentrations were considered negligible), and the ratio between biodegradable and non-biodegradable organic matter (BOD/COD) for influent and effluent of each WWTP see Tables S1 and S2 in Supplementary Material. The concentrations of nutrients in the raw wastewater and the actual effluent are based on measured data (Table S1) and complemented with data from a previous study (Table S2). Each data set was assumed to represent lognormal distributions, and the calculated parameters were used to define the probability distributions (Table S5). Random values of both ratios, assuming uniform distribution, were then used to calculate the concentration of available forms of nutrients (C_{AN}) in irrigation water and accumulation of available forms of nutrients ($A_{Ni\ K}$) in soil.

The dose of nutrients to soil per irrigation event (d_{NI}, in kg ha^{-1}) was calculated as

$$d_{NI} = V_I \times C_{AN} \tag{8}$$

where V_I = volume of water per irrigation event (m^3 ha^{-1}), and C_{AN} = concentration of nutrient in available forms in the irrigation water (kg m^{-3}). Equation 8 was slightly modified and used to calculate the dose of nutrients to soil in organic form per irrigation event as

$$d_{ON\ K} = V_I \times C_{OF} \tag{9}$$

where C_{OF} = concentration of nutrient in organic forms in the irrigation water (kg m^{-3}).

The same model (Equation 9) was used to estimate the accumulation of both N and P in the soil per irrigation event ($A_{Ni\ K}$, in kg ha^{-1}):

$$A_{Ni\ K} = d_{NI} - c_{N\ K} + d_{ON\ K} \times (c_{BOD\ K}/c_{COD\ K}) \tag{10}$$

where $c_{N\ K}$ = crop requirement of nutrient between the K_{th} and the K_{th+1} irrigation (kg ha^{-1}), $d_{ON\ K}$ = dose of nutrient in organic form from irrigation water at the K_{th} irrigation (kg m^{-3}), and $c_{BOD\ K}/c_{COD\ K}$ = proportion of biodegradable organic matter in water at the K_{th} irrigation. In the case of nitrogen, 25% of d_{NI} was subtracted in order to represent the nitrogen lost by nitrification/denitrification processes per irrigation (Barton et al. 1999). Finally, the nutrient accumulation probability during one crop season was estimated as the frequency of nutrient excess values ($A_{N\ K} > 0$) of each nutrient. The distributions, fit parameters and data used in models are shown in Table S6.

Monte carlo simulations

Since our risk models incorporate probability distributions, the Monte Carlo method (i.e.) was applied. This method consists of random sampling of input parameters from relevant distributions, here using 10,000 iterations, and generating distributions of the outputs (microbial and nutrient excess risks). The risk calculations were performed in Microsoft Excel.

Results

Management assessment of the WWTPs

The initial and normalised scores of the management assessment indicators are summarised in Table 3 and presented in full in Supplementary Material ('Management assessment'). Case 1-UFP, Case 2-UF and Case 3-P had the highest mean normalised scores (0.33, 0.55 and 0.42, respectively). Case 4-I and Case 5-I both had a mean normalised score of zero, as the systems were rated zero in all evaluations.

Regarding criterion 1 (Current performance), Case 2-UF met the discharge requirement for TSS but not for BOD (normalised score 0.5), while Case 3-P partly met both requirements (normalised score 0.5). Case 1-UFP partly met the discharge requirement for TSS, but not for BOD (normalised score 0.25).

Regarding criterion 2 (Technological potential), Case 3-P theoretically met health-based targets for wastewater reuse with regard to helminth eggs, but only partly with regard to FC (normalised score 0.75). Cases 1-UFP and 2-UF showed potential to remove helminth eggs to some extent, but did not meet the FC reduction target (normalised scores 0.25).

Regarding criterion 3 (Operation and maintenance), Case 2-UF performed best, receiving a normalised score of 0.90 and a score of 2 for four out of five indicators. Full-time technical and operational expertise is available year-round at this WWTP and all O&M activities in pre-treatment, the main processes and long-term are carried out according to the requirements of the specific technology, so it can perform all activities required for optimal O&M. The only shortcoming is lack of an adequate monitoring system, since the current system cannot measure in-situ parameters (e.g. temperature, pH, volume of biogas production, settleable solids and alkalinity) to ensure that the main unitary processes are working efficiently.

Table 3. Individual scores (scale 0 (non-functional) to 2 (performing well)) and normalised scores (scale 0 to 1 (optimal performance)) for management awarded to the case WWTPs.

N◦	Indicators	Case 1-UFP	Case 2-UF	Case 3-P	Case 4-I	Case 5-I
	Criterion 1 - Current performance					
1	Meets BOD discharge requirements in country	0	0	1	0	0
2	Meets TSS discharge requirements in country	1	2	1	0	0
	Normalised score for Criterion 1	**0.25**	**0.50**	**0.50**	**0.00**	**0.00**
	Criterion 2 - Technological potential					
3	Potential of current technology to reach the health-based target of 6 $\log_{10}$ pathogen reduction for unrestricted irrigation.	0	0	1	0	0
4	Potential of current technology to reach health-based target of ≤1 helminth egg per litre in the treated wastewater for unrestricted irrigation.	1	1	2	0	0
	Normalised score for Criterion 2	**0.25**	**0.25**	**0.75**	**0.00**	**0.00**
	Criterion 3 - Operation and maintenance					
5	Meets required level and availability of technical expertise needed for optimal O&M (technology-specific).	1	2	0	0	0
6	Performs required O&M activities and frequency in pre-treatment (technology-specific).	1	2	0	0	0
7	Performs required O&M activities in the main process units (technology-specific).	1	2	0	0	0
8	Performs required long-term maintenance activities in the main process units (technology-specific).	2	2	0	0	0
9	Has the required monitoring system to ensure optimal O&M (technology-specific).	0	1	0	0	0
	Normalised score for Criterion 3	**0.50**	**0.90**	**0.00**	**0.00**	**0.00**
	Mean normalised score	**0.33**	**0.55**	**0.42**	**0.00**	**0.00**

Case 1-UFP had the next-best O&M score (normalised score 0.50). It has operational staff year-round, but technical expertise only some months per year when required for maintenance (mainly UASB reactor and biofilters), which can result in neglect or delay of maintenance tasks. O&M activities regarding pre-treatment and the main processes are only partly fulfilled, but the long-term maintenance is satisfactory. There is no monitoring system sufficient for the type of technology used.

Cases 3-P, 4-I and 5-I scored 0 for all indicators in the O&M criterion. All have similar issues regarding operation, maintenance and monitoring. Case 3-P and 5-I do not have operators. Instead, staff working on drinking water supply systems must solve acute issues of, e.g. overflows or clogging in these WWTPs. In Case 4-I, the operator is present a few hours per week, to pump the raw wastewater into the Imhoff tank if the automatic pump is not working. The tank is also not emptied regularly as required. The Imhoff tank in Case 5-I is emptied once a year, or if it collapses due to the accumulation of solids.

Microbial risks

The QMRA results for lettuce consumption with the different wastewater scenarios studied is presented in Figure 1. The probability of exceeding the maximum additional disease burden of 10^{-4} DALYs person^{-1} year^{-1} for Enterovirus (dashed line in Figure 1) was found to be higher than 5% in three out of 15 wastewater sources assessed (Case 2-UF raw wastewater and theoretical effluent, Case 5-I actual effluent). No median was found to be higher than 10^{-4} DALYs person^{-1} year^{-1} and only the upper values of the actual effluent in Case 5-I were higher than the pre-existing disease burden (10^{-2} DALYs person^{-1} year^{-1}, solid line in Figure 1). The disease burden obtained for *Salmonella* spp. was the highest of the pathogens studied. The simulations for *Salmonella* spp. resulted in at least 75% probability of exceeding the threshold disease burden of 10^{-4} DALYs person^{-1} year^{-1} in 10 out of 15 wastewater sources assessed, and at least 25% probability of exceeding the pre-existing disease burden of 10^{-2} DALYs person^{-1} year^{-1}

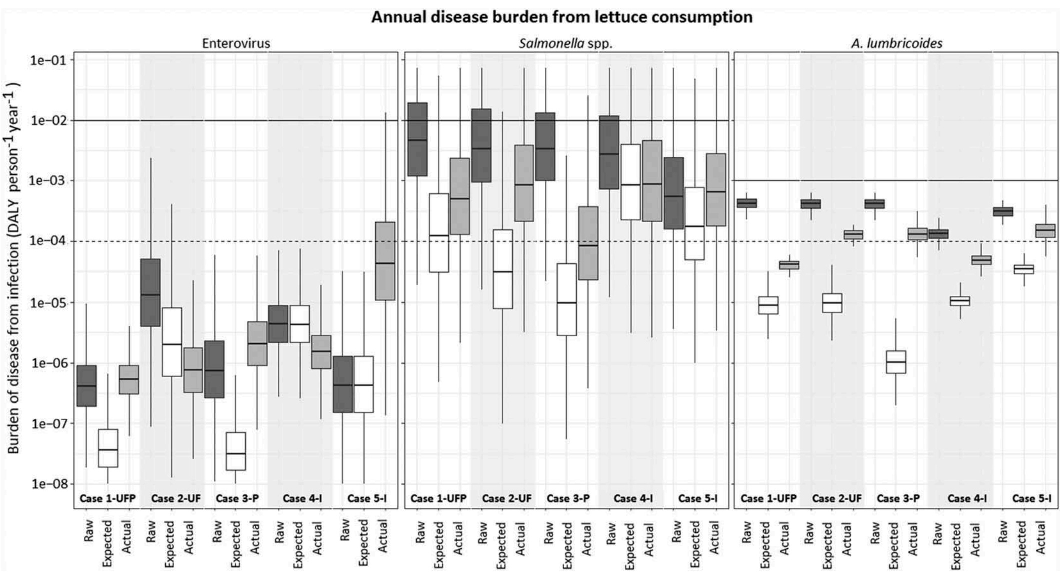

Figure 1. Estimated disease burden resulting from consumption of lettuce irrigated with raw influent (dark grey boxes), actual effluent (light grey boxes) and theoretical effluent (white boxes) from the five small-scale wastewater treatment plants studied (Cases 1–5), for Enterovirus, *Salmonella* spp. and *Ascaris lumbricoides*. The lower, medium and upper lines in boxes represent the 25th, 50th and 75th percentile, respectively; and the whiskers represent the 95% credible interval. The dotted line indicates the maximum additional disease burden permitted for wastewater reuse in developing countries. The solid lines represent the disease burdens from diarrhoeal diseases (for Enterovirus and *Salmonella* spp.) and intestinal nematodes (for *Ascaris lumbricoides*) reported for Bolivia by Pruss-Ustun et al. (2008).

in four out of the wastewater sources. Eight out of 15 disease burdens estimated for *A. lumbricoides* (both upper values and medians) were above 10^{-4} DALYs person^{-1} year^{-1}, but none was higher than the pre-existing disease burden.

All simulated *Salmonella* spp. and *A. lumbricoides* disease burdens with actual effluent were similar or higher than those obtained with theoretical effluent. For Enterovirus, the disease burden with actual effluent from Case 1-UFP, Case 3-P and Case 5-I was also higher than for theoretical effluent. The opposite (i.e. lower disease burden from actual than theoretical effluent) was found in Case 2-UF and Case 4-I.

Excess nutrient risks

Simulated accumulation of available nitrogen insoil is shown in Figure 2. For most scenarios, the 95th percentile ranged from 100-1000 kg N ha^{-1} while the median was <100 kg N ha^{-1}, indicating a high spread of the results towards high excess values (Figure 2; numerical results are presented in Table S7 in Supplementary Material). With regard to the medians, accumulation in soil with actual effluent was about 100-200 kg N ha^{-1} higher than with theoretical effluent, except for Case 5-I. Considering the percentage of simulations resulting in excess nitrogen in soil, it was found that i) accumulation with theoretical effluent was lower than with raw influent and actual effluent; and ii) accumulation in soil was greater with lettuce than with maize.

The simulations of available phosphorus accumulated in soil found that in all cases the 75th percentile was <100 kg P ha^{-1} and for several cases the 97.5th percentile was <100 kg P ha^{-1} both for maize and lettuce (Figure 3). Comparing the medians, most accumulation in soil was higher with actual effluent than theoretical effluent, except in Case 3-P for maize, where the values can be

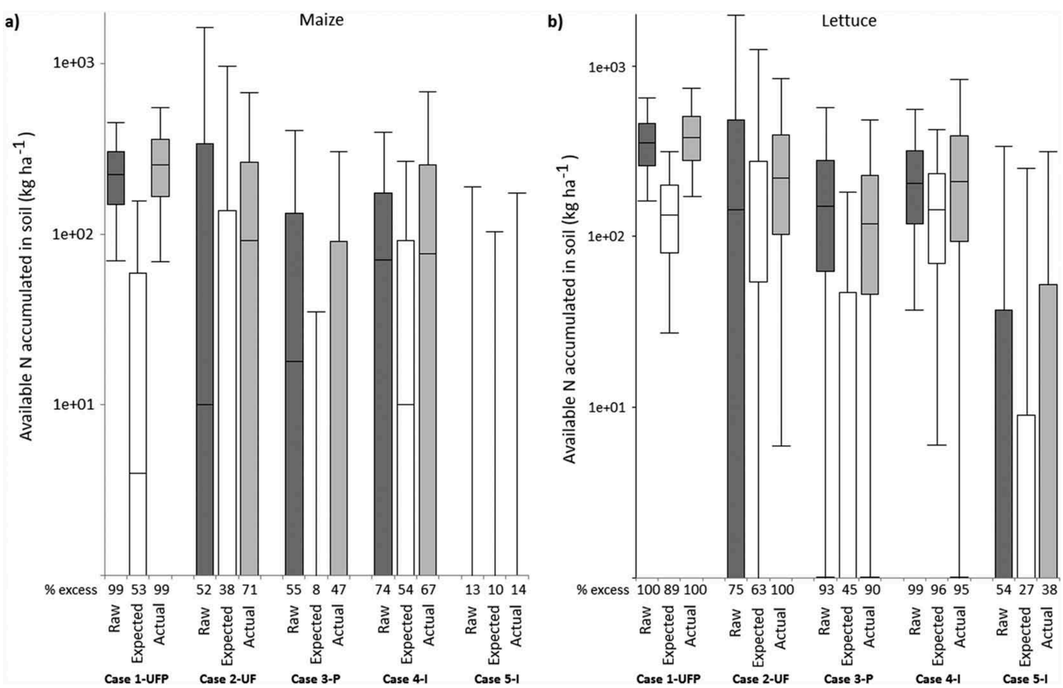

Figure 2. Simulated concentrations of available nitrogen (N) in soils irrigated with raw influent (dark grey boxes), actual effluent (light grey boxes) and theoretical effluent (white boxes) from the five small-scale wastewater treatment plants studied (Cases 1–5) after one season of cultivation of (a) maize and (b) lettuce. The medium and upper lines in boxes represent the 50th and 75th percentile, respectively; and the lines above the boxes represent the 95% credible interval. The numbers below the horizontal axis indicate the percentage of simulations resulting in positive values (excess N in soil).

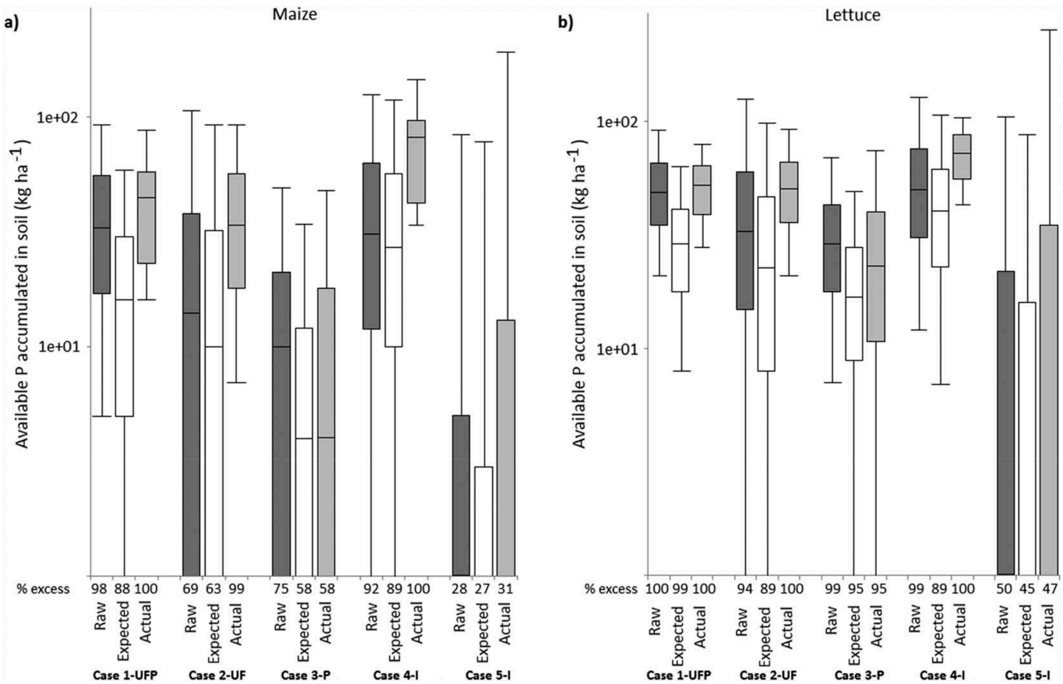

Figure 3. Simulated concentrations of available phosphorus (P) in soils irrigated with raw influent (dark grey boxes), actual effluent (light grey boxes) and theoretical effluent (white boxes) from the five small-scale wastewater treatment plants studied (Cases 1–5) after one season of cultivation of (a) maize and (b) lettuce. The lower (if visible), medium and upper lines in boxes represent the 25th, 50th and 75th percentile, respectively, and the lines above the boxes represent the 95% credible interval. The numbers below the horizontal axis indicate the percentage of simulations resulting in positive values (excess P in soil).

considered equal (for numerical results, see Table S8 in Supplementary Material). The probability of excess phosphorus in soil was higher for lettuce (89-100% for Cases 1-UFP, 2-UF, 3-P and 4-I) than for maize crops (58-100% for Cases 1-UFP, 2-UF, 3-P and 4-I), see Figure 3.

Discussion

Management assessment

The management assessment revealed that the basic requirements for BOD and TSS removal are not met, or are only partly met, in all WWTPs studied. Based on general influent composition and theoretical removal rates, the assessment also indicated that only the technology implemented in Case 3-P has the potential to reduce the concentrations of helminth eggs and FC to the limits set by World Health Organization (WHO) for safe reuse of wastewater in agriculture. The assessment of the O&M indicators indicated the potential to improve the current performance of the five WWTPs. It also indicated that Case 3-P can meet both the national discharge limits and the WHO limits for reuse in agriculture with O&M practices improved.

In the WWTPs with the lowest O&M score (Case 3-P, Case 4-I and Case 5-I,), the issues due to poor O&M in the process units were evident in on-site observations (e.g. visible clogging, excessive accumulation of sludge, blockage in process unit inlets). In the WWTPs with higher O&M scores (Case 1-UFP and Case 2-UF), issues (e.g. periodic organic overloading/underloading, suboptimal design of the units) were only identified through interviews with managers and operators. Monitoring of WWTP performance is important for optimal O&M and for confirming the removal efficiency of the system.

In Case 1-UFP and Case 2-UF, the requirement for TSS discharge was partly and fully met, respectively, but the BOD limit was exceeded (Table 3). In Case 1-UFP, the latter was probably caused by overloading, as the interviews revealed occasional increases in hydraulic and organic loading rates to that WWTP. Thus, more systematic monitoring of incoming flows to Case 1-UFP is needed to divert overflows, so the UASB reactor functionality is not impaired. Although a tertiary treatment process (maturation pond) is used in Case 1-UFP, the sub-optimal O&M seems to affect its performance. Case 2-UF performed better than Case 1-UFP regarding O&M activities and removal of TSS, but the technology implemented at Case2-UF is theoretically not sufficient to fully meet the WHO limit for reuse in agriculture.

In Case 3-P, removal of both BOD and TSS partly meets the discharge requirements, despite the low scores it obtained for O&M. Moreover, the technology implemented (stabilisation ponds) is theoretically able to meet the WHO limits for reuse in agriculture at least for FC. Stabilisation ponds are a low-cost technology popular in developing countries for their easy O&M and can remove up to 6 log units of pathogens from raw wastewater (Jiménez et al. 2010; Mara 2013). Moreover, stabilisation ponds have shown high removal rates for parasite eggs (e.g. Ascaris lumbricoides), i.e. ≥99% (Sharafi et al. 2012). However, stabilisation ponds could have low removal rates for nitrogen and phosphorus (Pirsaheb et al. 2014). On-site observations revealed that lack of regular O&M at Case 3-P leads to accumulation of solids on the surface of the stabilisation ponds, causing dead zones (i.e. reduced retention time) and interfering with treatment mechanisms related to sunlight exposure. Despite the reduced retention time, TSS and BOD are probably removed as a result of the large volume of the stabilisation ponds, as some settling of particles and biodegradation of organic matter still occurs.

Cases 4-I and 5-I, with Imhoff tanks, performed poorly in all management criteria. They are designed to reduce the concentration of TSS by up to 50% and BOD by up to 35% (Cossio et al. 2017), but this not occurring, probably due to the lack of O&M activities. The Imhoff tank technology is also not sufficient to meet health-based targets for reuse of effluents in agriculture.

Microbial and ecological risks can be theoretically reduced by using technologies that provide an adequate level of treatment (e.g. secondary and tertiary) (Jaramillo and Restrepo 2017). However, well-functioning pre-treatment and primary treatment are critical, since they make secondary and tertiary treatments effective. Case 1-UFP, with tertiary treatment, could potentially perform better than it currently does, but the type of technology (i.e. UASB reactor) and the level of difficulty in operating and maintaining it may hinder its full potential. More resilient technologies, such as the stabilisation ponds in Case 3-P, can achieve partly sufficient removal even without adequate O&M.

Effects of WWTP management on risks

Regarding microbial risks, Enterovirus levels were below the permissible additional disease burden for wastewater reuse even for non-optimal O&M in all cases. For *A. lumbricoides*, optimal O&M is essential to lower the risks in Case 2-UF, Case 3-P and Case 5-I. For *Salmonella* spp., even with optimal O&M practices, the risk level could not be brought below the permissible level. The only difference in the inputs to these risk simulations was the pollutant concentration in the different wastewater sources (i.e. raw wastewater, actual effluent and theoretical effluent). In principle, the differences in risk with actual and theoretical effluent originate from issues in WWTP process units due to poor management. However, uncertainties in the raw data are likely to contribute to some extent, as small-scale WWTPs lack regular records on influent/effluent composition and flow and the sample size in the current study was limited.

Improvement of O&M activities in Case 1-UFP would decrease the risk of excess nutrients in maize and lettuce cropping, in particular the risk of excess soil nitrogen following maize (from 99% to 53% probability, with median excess nitrogen decreasing from about 130 to less than 10 kg N ha^{-1}).

Regarding microbial risks, Enterovirus and *A. lumbricoides* levels were below the permitted additional disease burden for wastewater reuse, even with non-optimal O&M. However, for *Salmonella* spp., even optimal O&M practices cannot bring the risk level to below the threshold. The general management assessment also indicated that the present technology is not sufficient to reach health-based targets for reuse of wastewater in agriculture. In particular, hydraulic and organic loads need to be monitored to avoid overflow and collapse of UASB reactors.

Case 2-UF was found to have the best O&M practices, but the risk level regarding Enterovirus and *Salmonella* spp. was not acceptable for lettuce irrigation, even with the technologies working at full potential. Assessment of the technological potential showed that the target for FC was also not likely to be met. A tertiary treatment might thus be needed at Case 2-UF to enable safe reuse of the effluent in irrigation regarding Enterovirus and *Salmonella* spp. Regarding *A. lumbricoides*, with better O&M practices than currently implemented, it may be possible to reduce the microbial risk associated with lettuce irrigation to an acceptable level. Regarding nutrient excesses in soil, improved O&M could not reduce the risk levels sufficiently, although the probability of excess soil nitrogen following maize cropping could be reduced from 71% to 38%. Improved monitoring at Case 2-UF is thus recommended to allow for adjustment to treatment conditions, so that the five treatment lines can operate optimally.

In Case 3-P, the general management assessment indicated that microbial and probably ecological risks can be reduced if O&M practices are improved and a monitoring system is implemented. Based on the risk simulation results, optimal O&M can lower the microbial risk levels for *A. lumbricoides*, but not *Salmonella* spp., to below the permissible disease burden (technological potential is sufficient for helminth eggs, but only partly sufficient for FC). Better O&M practices can reduce the risk of excess soil nitrogen significantly and the risk of excess phosphorus to a lesser degree.

For Case 4-I, risk levels for Enterovirus and *A. lumbricoides*, but not *Salmonella* spp., were acceptable for both actual and theoretical effluent. The microbial risk levels for Enterovirus were lower for actual effluent than theoretical effluent (Figure 1), while the converse (as would be expected) was true for *A. lumbricoides*. As the WWTP is clogged, water only flows occasionally in Case 4-I, i.e. when it is pumped into the tank as the level in the storage tank reaches a certain level. Thus, wastewater is retained in the clogged tank and exposed to the sunlight, until it is removed by the next pumping. It can be speculated that such exposure to sunlight inactivates both *Salmonella* spp. and Enterovirus (WHO 2006).

For Case 5-I, all microbial risk levels were unacceptable for actual effluent, but acceptable regarding Enterovirus and *A. lumbricoides* for theoretical effluent. For Enterovirus, risk levels with actual effluent were higher even than with raw wastewater, possibly because the WWTP is connected to a health centre with almost 10-fold the population-equivalents (p.e.) of the small town for which the WWTP was designed (4660 p.e. and 575 p.e., respectively). This WWTP thus possibly receives a high load of pathogenic contaminants that accumulate in the Imhoff tank by particle settling and, as it is not regularly emptied, get flushed out with high flows, especially in the rainy season.

The excess nutrient risks for both actual and theoretical effluent in Case 5-I were significantly lower than in Case 4-I. This is probably due to dilution, as the raw wastewater flow per capita in Case 5-I (0.09 m^3/p.e.-d) is twice that in Case 4-1 (0.04 m3/p.e.-d). In both cases, excess nutrient risks were higher for actual than for theoretical effluent and for some cases higher for actual effluent than for raw wastewater (Figure 2, Figure 3). A possible explanation for the latter is that occasional high flows through clogged tanks in both WWTPs are likely to detach clogged particles, adding nutrients to the outflow and occasionally producing an effluent with higher contaminant load than the inflow (Table 4).

Quantitative risk estimations

In general, the highest microbial risks were obtained for *Salmonella* spp., followed by *A. lumbricoides*. *Salmonella* spp. is a zoonotic disease so there is an additional risk of disease transmission to animals, restricting the use of the water for irrigation of pasture and grass production. The results indicate that there are unacceptable microbial risks from irrigation of lettuce with actual effluent from Case 5-I (Enterovirus), from all sites (*Salmonella* spp.) and from Cases 2-UF, 3-P and 5-I (*A. lumbricoides)*. There are also unacceptable microbial risks from irrigation of lettuce with theoretical effluent from Case 2-UF (Enterovirus) and from all sites (*Salmonella* spp.).

Regarding the risk of excess soil nutrients, the results indicate that there are unacceptable risks (probability >5%) from irrigation of maize and lettuce crops with actual or theoretical effluent from all sites. The risks of accumulated nutrients are higher with lettuce than with maize, owing to lower tolerance of lettuce to water stress. Lettuce requires much more frequent irrigation than maize and the total amount of water applied to lettuce by furrow irrigation is higher (see Supplementary Material, Table S6). Vitousek et al. (2009) present annual excess values for different regions and agricultural systems, ranging for N from −52 to +227 kg N ha^{-1} and for P from −9 to +53 kg P ha^{-1}, and argues that policymakers should be aware of the need to implement regulations to decrease eutrophication risks.

The simulated risks were generally higher throughout for actual effluent than for theoretical effluent (Figure 1, Figure 2, Figure 3). This can be explained by poor O&M of the WWTPs, but also by some assumptions used in the risk assessment. For example, virus removal in UASB reactors has not been thoroughly studied (only two studies were found: Ottoson et al. (2006); Symonds et al. (2014)) and the values reported were considered not significant (>1 $\log_{10}$). Therefore, a conservative value of zero removal was assumed calculating theoretical removal for UASB reactors, which can explain the significantly lower concentrations and risks of Enterovirus for actual effluent than for theoretical effluent in Case 2-UF (Figure 1). Another assumption concerned the microbial indicators to pathogen ratio used for Enterovirus and *Salmonella* spp. In the case of Enterovirus, irrigation with most influents (i.e. raw wastewater) resulted in risks below the maximum additional disease burden (Figure 1). However, the assumed coliphage to Enterovirus ratio may have underestimated the actual concentrations of Enterovirus in the water sources. For *Salmonella* spp., irrigation with all water source scenarios, even with theoretical effluent, resulted in risks exceeding the maximum disease burden set for developing countries (Figure 1). In this case, it is possible that the assumed ratio of FC to *Salmonella* spp. overestimated the actual concentrations of *Salmonella* spp. The use of microbial indicators to estimate pathogen concentrations is still a matter of debate due to the uncertain correlations, but it is widely accepted in a developing country context where data about pathogens are generally lacking (World Health Organization WHO 2006).

Alternatives for risk mitigation

Differences in microbial risk levels for actual and expected effluent were linked to O&M. Regarding Enterovirus, an optimal O&M would reduce the risk for Case 5-I to at least 95% probability of being below 10^{-4} DALYs $person^{-1}$ $year^{-1}$. However, for *Salmonella* spp. optimal O&M would not reduce the risks for any of the five WWTPs to at least 95% probability of being below 10^{-4} DALYs $person^{-1}$ $year^{-1}$. Thus, new technologies need to be implemented or other risk-reducing measures are needed for *Salmonella* spp. Although the assessment of technological potential for helminth eggs indicated that only Cases 1-UFP, 2-UF and 3-P could reach the general requirements, the site-specific risk estimations for *A. lumbricoides*, indicated that optimal O&M lowered the risk to acceptable levels in all cases.

For nutrients, given that we accept a probability of 5% of getting excess nitrogen and phosphorus accumulation, no WWTP can deliver a theoretical effluent for irrigation which fulfils this risk level. However, for Case 3-P and Case 5-I, the risk was rather low for excess nitrogen from maize growing (8% and 10%, respectively). Thus, better O&M is not enough to reduce excess nutrient risks to an acceptable level. Instead, the WWTPs might need to be upgraded in order to remove nutrients to the extent that it is possible to reuse the effluent for irrigation while avoiding excess nutrients in the soil.

Thus, a way to reduce contaminants in the effluent is by upgrading existing WWTPs by adding new process units or implementing a more appropriate design. There is extensive literature about available treatment processes with high removal efficiencies of both pathogens and nutrients from wastewater, but comparison and selection of such upgrades were outside the scope of this study. However, the local resources available in terms of technical expertise and financial resources should be part of the decision-making processes on WWTP upgrading, so that the chosen technology can be operated at its full potential (Cossio et al. 2017). It is also important that the treatment process is designed with the safe use of the effluent for irrigation purposes as a design criterion.

Another alternative to reduce the risks is to implement on-farm treatment of wastewater as a low-cost alternative to reduce the pollutant load in water before irrigation. Such treatment is based on similar processes as in conventional wastewater treatment, but with lower removal efficiency (Keraita et al. 2014). The underlying principle is a multi-barrier approach to wastewater reuse (WHO 2006). Several on-farm treatments are available, such as ponding in on-farm irrigation infrastructure and filtration in on-farm trenches (Keraita et al. 2014). However, in order for treatment to be implemented and functional, farmers need sufficient information and awareness of the benefits. They also need to be informed about crops for which wastewater irrigation should not be used according to the WHO (2006).

Conclusions and recommendations

This study reached the following conclusions and recommendations:

- Microbial risk levels can be reduced to acceptable levels with optimal O&M of existing WWTPs. However, further treatment steps are needed to reduce risks from *Salmonella* spp to acceptable levels in the studied WWTPs.
- Ecological risks from nitrogen and phosphorus accumulation in soil could be reduced with optimal O&M at the five WWTPs, but not to the levels set in this study (95% probability of no excess). Therefore, additional treatment is needed to reduce the risk of eutrophication of groundwater and/or surface water.
- Robust technologies (i.e. stabilisation ponds) and sufficient level of treatment (i.e. primary, secondary, tertiary) are crucial in achieving removal efficiencies and thus reducing risks. In contrast, high-performance technologies (i.e. UASB reactors) might be insufficient to reduce bacterial and ecological risks even under optimal O&M. These factors should be considered when planning WWTPs.
- Operation, maintenance and monitoring of WWTPs should be carefully considered in the planning phase of WWTPs implementation in a developing context in order to achieve safe conditions for irrigation reuse.
- In developing countries, when upgrading of existing technologies is not feasible, other alternatives to mitigate microbial risks, such as on-farm treatment or training farmers in improved agricultural practices, should be tested and evaluated.
- Future studies should assess the impact of O&M practices of WWTPs in developing countries on human health and ecological risks from wastewater irrigation associated also with other constituents in treated wastewater, e.g. pesticides, pharmaceuticals and microplastics.

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